N90-29795

AN ADVANCED TELEROBOTIC SYSTEM FOR SHUTTLE PAYLOAD CHANGEOUT ROOM PROCESSING APPLICATIONS

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ABSTRACT

Ground processing of the Space Shuttle and its associated payloads at Kennedy Space Center is extremely time consuming and costly. Automation of both physical and information system processing can significantly reduce costs, processing time, and operational hazards to human technicians and space hardware, and improve reliability. Extensive efforts by NASA-KSC and its associated shuttle and payload contractors to implement automated systems are now ongoing. One particularly attractive application, which is a crucial operation in need of improvements, is payload and shuttle processing at the Payload Changeout Room (PCR). The PCR located at each of the two shuttle launch pads is a large clean room mounted on the Rotating Service Structure. All payloads are partially processed, accessed and in some cases transferred to the shuttle bay from this room.

Unfortunately, the current handling mechanism and platform system does not provide completely flexible access to all payloads and critical Shuttle bay locations. Thus, either human technicians are placed in hazardous positions, or specialized fixtures, scaffolds and lifting devices are used. These alternatives all increase cost, possibly increase payload exposure to potential damage and reduce efficiency, flexibility and overall cleanliness. Thus, to potentially alleviate these inherent difficulties, a teleoperated, semi-autonomous robotic processing system for the PCR is now in the conceptual stages.

A clean room manipulator arm, custom designed for the PCR, will perform basic processing tasks such as inspection, insertion and removal of small items. A highly redundant avoidance system will be incorporated to guarantee that collisions with delicate space hardware are avoided. A redundant arm (greater than 6 DOF) will likely be required due to the large workspace which is extremely cluttered and constrained when a payload is in the shuttle bay or PCR. The system will be driven by high-level user-entered commands or through a manually operated joystick. Thus, a complex planning and reasoning system based on Artificial Intelligence technology will be required. The primary challenge in this project is the integration of leading edge automation technologies now available. The integration and further development of the required technologies is now being accomplished through a joint NASA JPL/KSC demonstration program which began in 1988. This 3 year program will demonstrate actual PCR tasks using a full size mock-up, actual flight hardware and the ASEA IRB90 robot arm located at KSC's Robotic Applications Development Laboratory. The complete PCR robotic system as currently conceived is described here. Critical design issues and the required technologies are discussed.

1. INTRODUCTION

A number of ground processing operations at KSC could be improved through automation. Recently a study was conducted to determine where automation may benefit ground processing of payloads including the Space Station, [1]. The reasons for introducing automation include the reduction of hazards to payloads and processing personnel, reductions in operational costs and processing time. In addition, automation will help to improve processing reliability, verification and documentation.

One of the best examples of physical processing automation at KSC is the cleaning and refurbishment of the Solid Rocket Booster's nose cone, instrument module, and aft skirt. For this application, the justifications are easily identified: the process is repeated for two SRBs for each mission, it eliminates the exposure of humans to a hazardous environment, produces more consistent results, and has provided a significant cost savings to SRB refurbishment [2].

For most of the automation applications needed for payload processing, full autonomy is not possible due to current state-of-the-art capabilities of robots and controllers. Instead of totally replacing the human, his physical skills and capabilities should be augmented through automation. Most payload processing robotic applications, require a balanced combination of computer intelligence and human reasoning and control. The Payload Changeout Room (PCR) is an ideal candidate for robotic technology due to the time constraints, criticality of operations, current difficulties associated with payload access, cleanliness requirements and associated cost of operations.

The major challenge of implementing advanced automation systems is the integration of newly developed technologies including AI planning and reasoning systems, advanced sensory perception, telepresence interfaces, obstacle avoidance and redundant arm control. Even though the PCR telerobotic system will require most of these advanced technologies, the program risk is not great. All the technologies will be demonstrated before this system is fully designed and implemented, with the exception of the redundant arm control.

1.1 Launch Pad Operations

A brief description of launch operations is required to understand the function of the PCR. The PCR is a self contained clean room located on the Rotating Service Structure (RSS) at the launch pad, see Figure 1. The RSS is attached to the Fixed Service Structure (FSS). The FSS provides access to the shuttle, SRBs and external tank. The RSS rotates up to the shuttle before launch, and is rotated away from the orbiter prior to lift off. The PCR provides access to payload bay and is the interface used to transfer vertical payloads to the orbiter.

Payloads are brought out to the pad in a vertical canister having the same dimensions as the orbiter payload bay. The canister is lifted off a transporter and raised approximately 80 feet, to the level of the PCR. Seals on the PCR provide an air tight bond between the canister and PCR. The doors to the PCR and cannister are then opened, and the payload is then transferred from the canister to the orbiter. The transfer is accomplished using the Payload Ground Handling Mechanism (PGHM) which lifts the payloads by their attached trunnions and retracts back into the PCR. The PGHM is actually a two degree-of-freedom device with lifting and translating capabilities. Once the payloads are secured on the PGHM, the doors to the cannister and PCR are closed, the cannister is lowered, and the RSS is rotated towards the orbiter. Once the PCR is against the orbiter, the doors of the PCR and orbiter are opened.

At this time the final preparations are made to payloads. The PGHM then translates out and lowers the payload into the orbiter bay. The trunnions attached to the payloads are secured in the orbiter fittings and final closeout testing is completed. After all processing is completed, closeout photos are taken and the doors to the orbiter and PCR are closed. The RSS is then rolled back and final launch preparations occur.

1.2 PCR Description and Processing Tasks

The PCR is an 80 foot tall Class IV (<10K 0.5 micron particles/foot3) clean room which provides limited access to the payloads. Platforms are fixed at various levels, approximately every ten feet in height. These platforms are extended as required towards the payloads in the orbiter. Often, these extended platforms do not provide the necessary access, so auxiliary platforms are attached to the original platforms with 'C' clamps, see Figure 2. These auxiliary platforms are commonly called 'diving boards'. These devices do not provide complete access to the payload interfaces in all instances due to their location. In addition, the diving boards do not provide safety rails and have limited load capabilities, which may expose the payload technicians to undesirable working circumstances.

The problem of access has been addressed in the past by erecting temporary scaffolding in the PCR and more recently by constructing special purpose access hardware in the PCR. The scaffolding has several advantages in that it is completely portable and reconfigurable. The major disadvantage is that during the erection of the scaffolding, the payloads are susceptible to damage. The sections of scaffolding are tethered to personnel who then climb and assemble the sections. This is a difficult task under any circumstance, but in the constrained environment of the PCR, this task becomes very challenging. By constructing special purpose access platforms, many of the difficulties associated with the original access platforms or additional scaffolding are eliminated. However the cost for these assemblies are high, and they are designed to be used only once or twice and then they are dismantled and scrapped. Recently, approximately $750K has been designated for the special access structures for the Magellan and Galileo missions. This cost is typical.

A practical alternative to the previous methods is a dedicated robot system within the PCR. A flexible manipulator system could provide much greater access to the payloads, be able to operate in highly constrained environments, and handle hazardous materials. This robot would have to be specially designed to meet the many requirements of the PCR environment. Requirements include clean room operation, dexterous motion capability, and a high degree of safety and reliability.

2. BACKGROUND

Two specific driving forces have led to the highly positive consideration of an actual robotic system implementation at the PCR. First, the SS Strategic Plans and Programs Office-Advanced Development Program is sponsoring a joint JPL/KSC remote telerobotic demonstration program to integrate and advance a number of technologies that will be required for successful SS robotic applications. Secondly, there is a significant need for improvements in the current methods used for processing payloads at the shuttle launch pad. Improved, more flexible access to payloads is required to reduce the need for costly access platforms and fixtures, and eliminate the use of particulate generating cranes and lifting devices. A telerobotic demonstration program is currently being developed to meet the two tasks described above and will be described in this section.

2.1 Current Demonstration Program

In September 1988, JPL and KSC realized a common need and interest in a joint telerobotics program. JPL was interested in demonstrating remote teleoperation with induced time delays. KSC was interested in applying the technology to actual ground processing applications. By combining capabilities and resources of JPL and KSC, a leveraged program has evolved with an overall benefit to both current ground processing operations at KSC and meet the long range goals of on-orbit telerobotics for Space Station. The first year of a planned three year program is currently underway. A single application will be demonstrated this year.

Improvements in the software to meet the stringent requirements of the users in the PCR, hardware improvements to the user interface to provide real-time simulation of robot motions, the development of advanced proximity systems to improve the reliability of obstacle avoidance will be implemented in years 2 and 3. More advanced applications will also be demonstrated.

2.2 Demonstration System

The remote telerobotic test-bed will consist of three major components, a user interface and computer control hardware at JPL and a manipulator at KSC. Three leased 9600 buad serial communication lines will be used to connect the user interface and computer control hardware located at JPL to the robot located at KSC, see Figure 3. One line will be used to provide direct voice communication between the remote sites and the other two lines will be used to transmit compressed video images to JPL and provide two way robot communication, respectively.

The user interface at JPL resides in a Symbolics 3640 AI workstation. Using a menu driven, high level robot language, the operator is able to command the robot. The operator is able to preview robot motions with a graphic simulator on the Symbolics, observe joint positions and the natural language description of the current task being processed, see Figure 4. The Symbolics also does the task planning and reasoning and maintains the CAD model of the operational environment for obstacle free path planning.

The Symbolics machine is connected to a uVAX computer at JPL via a DECNET point-to-point connection. The Sensing and Perception module, and the Run-time Controller module are both located on the uVAX. The Sensing and Perception software is used to receive and reduce sensor information, and Run Time Controller outputs joint level robot commands. The uVAX at JPL is connected to the uVAX at KSC through a pair of leased serial lines. The uVAX at KSC is used to grab and compress images from a robot mounted video camera, and feedback joint positions from the robot and receive and execute robot motion commands via joint coordinates.

For direct teleoperation, a Symbolics computer will be installed at the KSC site, see Figure 5. The existing uVAX at KSC will then be directly connected to the Symbolics via a Decnet connection. The appropriate software will be copied from the computers located at JPL and loaded on the respective computers at KSC. The direct teleoperation scenario is preferable for testing the control software. Also for demonstration purposes, it would be more effective for the user/operator to see the response of the robot directly.

The manipulator located at KSC is an ASEA IRB-90, a six axis serial device with DC actuators. The ASEA IRB-90 has a 200 pound capacity, a 12 foot reach and a repeatability of 0.010 inch. It is located on a 30 foot track, and motion control along this track is provided by the robot controller.

2.3 Demonstration Applications

The first phase will demonstrate the capabilities of the user interface and controlling software. This will be done with the user interface being developed by JPL and ASEA IRB-90 robot at KSC. The potential users of the system (Shuttle Payload Operations) requested a realistic demonstration platform so that the telerobotics system could be realistically tested on actual flight hardware before being implemented in the PCR. The users recommended several pieces of demonstration hardware including a Payload Assist Module (PAM) Cradle, see Figure 6, and a Mission Peculiar Experiment Support Structure (MPESS). These two items were selected because of their geometry and constrained internal space. The users felt that if the robot could successfully navigate through such a constrained environment without hitting obstacles, then it could be easily used on less restrictive payloads, [3].

Approximately ten telerobotic applications have been identified by the users in the PCR and these include: component inspection, close-out photography, sharp edge inspection, lanyard identification and grasping, non-flight hardware identification, payload bay protective liner removal, insertion and removal of Quick Disconnects (QDs), and insertion of small items before closeout. These tasks are listed in order of increasing difficulty [3].

The first three tasks are strictly non-tactile tasks and require less sensory information and control software than the other tasks. The lanyard identification and grasping was included because it is a high priority item among the users and requires no direct contact with the rigid objects. The lanyards are attached to lens caps and other covers which must be removed before flight. Some of the lens caps and covers are currently designed for automation, and the others will be modified so that the robot may easily remove them by simply grasping the lanyard and pulling away from the payload [3].

The remaining applications are more difficult because they require some form of force feedback to the controller, or to the operator using force feedback joysticks. These tasks are currently scheduled to be accomplished in the second and third years of the program [3].

3. CRITICAL TECHNOLOGIES

A robot system located in the PCR must perform a wide range of tasks if it is to be cost effective, and well received by processing personnel. The highly constrained, delicate environment and difficult tasks necessitate the need for a system with a number of advanced capabilities. The PCR environment is vastly different than typical manufacturing applications. The required work area is highly cluttered and will contain extremely expensive, critical flight hardware and ground support equipment. Not only is the equipment critical, once it has reached the PCR a great deal of processing time has been expended and it is the last step in the payload launch flow. Thus, any damage would be extremely costly and significantly affect the launch schedule.

In order to implement a robotic system with the required capabilities a number of advanced technologies will be required. Considering the current capabilities of robotics and AI technology, the only way to accomplish the required tasks in a safe and reliable way is to provide a supervised, human augmented system. Human intelligence must be used to guide the planning process and react to uncertainties associated with unknown objects in the facility.

The most crucial elements necessary for the successful implementation of a robot in the PCR are a highly flexible, easy to use human interface which requires no previous robot programming knowledge, and fail safe methods to assure collision free motions of the robot. The critical technologies required to provide the needed capabilities include high level robot control languages, 3D object recognition and location vision systems, task scheduling, path planning, proximity sensing, collision avoidance, control of redundant manipulators, telepresence and force control. These technologies, with the exception of redundant manipulator control, have all been addressed by past research efforts and are currently being refined in the joint KSC/JPL PCR telerobotics demonstration program. Each of the required technologies are described briefly below.

3.1 Obstacle Avoidance Technologies

Obstacle avoidance must be guaranteed in a redundant fashion when working with sensitive flight hardware at the launch pad. Collisions of any links of the robot arm, end-effector, or tooling with any object in the work area must be avoided under all circumstances. This can be accomplished using a high level controller which creates obstacle free path plans based on stored and real-time knowledge of the working area. In addition all motions and tasks will be graphically simulated and approved by human operators.

To insure maximum reliability, the system will incorporate a triple redundant obstacle avoidance system. Primary obstacle avoidance path planning will be performed by a control computer using CAD graphic models of all payloads, PCR, ground support equipment and the Shuttle bay. CAD models for the launch facilities and a majority of the payloads are available and will be stored in the control computer during each mission. In addition to the static data a 3D vision system will be used to identify the shape and location of unknown or moveable objects (antennas, valves, doors, holding fixtures etc.). This data will be used to update the models before a path is planned. In addition to these two systems an independent hardware based collision detection system will automatically shut down the system before an impending collision.

The obstacle avoidance path planning technology will be based on the techniques being implemented in the demonstration program (see Section 2.2). The path planning method developed at NASA-JPL, described in [4], is based on the free-space techniques originally developed by Lozano-Perez [5]. The technique has been modified however, by representing all objects in the workspace, as described by the stored geometric model, in terms of the manipulator joint coordinates. All paths are then planned in this joint coordinate representation which is referred to as the configuration space. The method is best described by the following procedural description:

1. The manipulator workspace is discretized into a set of p joint values for each of the N axes of the manipulator. This results in a table of N^p configurations.

2. The discretized configuration space is then searched to determine if any link or the end-effector interferes with any object in the workspace. If an interference occurs the node is marked as occluded space.

3. The above binary table is created and stored off-line. Online path planning consists of determining a path in the N-dimensional space between the current and desired location which contains only non-occluded nodes (free-space).

Generating the binary workspace obstacle map is a numerically intensive operation which takes considerable time. Thus this technique is only practical for relatively static work areas. The primary advantage of this method is that a collision free path for the entire arm is created. There are a number of other advantages of working in the joint coordinate representation which are discussed in [4].

Using the above technique which requires a completely static and known model of all objects accessible by the PCR robot is not adequate. The model and corresponding obstacle avoidance map must be updated due to moveable objects, tools and fixtures. This will be accomplished using a 3D object recognition and location vision system. A stereo vision system located on the robot will be used to recognize and determine the shape and location of known and arbitrary objects. This information will be used to update the CAD model of the work area used by the planning system. Image processing 3D recognition and location techniques are now in development at JPL [6] and a number of other laboratories. Although this is leading edge technology, based on past demonstrations at JPL, it is expected that a satisfactory system will be developed in the demonstration program.

One critical issue not addressed above is the availability of CAD graphic models of all objects in the PCR during processing. Models of the PCR are being developed now and a model of the Shuttle bay already exists. However, these models exist on various computer systems using different 3D graphic representation standards. Most of the payloads also exist in digital form. The critical technology therefore is the ability to transport a wide variety of CAD models into a common representation which can be accessed by the high-level computer. Current plans are to transfer all models into the Interim Graphic Exchange Specification (IGES) standard. However this may be inadequate for 3D models and advances in this technology may be required.

Hardware based collision detection technology is also required to avoid unexpected collisions and performance. A proximity sensing system capable of providing the distance between any point on the manipulator arm and the closest object of any material must be implemented. A large number of reliable proximity sensors must be mounted on the arm and integrated into a single, fast reacting system. Potential sensor candidates include sonar, radar, laser triangulation, coherent laser radar, and highly compliant contacts. This technology has not been demonstrated in large scale. However there is some direction in the Flight Telerobotic Servicer (FTS) program to provide a system of this type.

3.2 High Level Task Planning, Reasoning and Human Interface

A high level programming language and user interface will be required for the efficient operation of a robot in the PCR. This system should have the ability to plan, initiate and schedule complete operations based on generic input commands, and provide high resolution graphic simulations of all planned operations for review. The system should also be able to reason over a set of rules and guidelines which assures that all processes and tasks will be performed according to set procedures and Operational Maintenance Instructions (OMI).

A high level or generic input interface is required to assure that operators with little robot programming experience are able to quickly and easily program and operate the robot system. The high level programming system will primarily alleviate the need for tediously programming entire paths of end-effector positions and various tool commands. Using this interface the operator would teach or operate the system by selecting specific actions or operations from a menu to be performed on a given payload or piece of equipment, on a specific subsystem. For example, the operator would select 'INSPECT' from a menu (Inspect, View, Insert, Remove, Move To, Open etc.), then from another menu the device 'PAYLOAD' and from a sub menu 'FUEL UMBILICAL'. The task planner would then determine the complete sequence of events necessary to carry out the task based on procedures and guidelines stored in a data base, and would provide an obstacle free path for the entire robot.

This capability will be based on an advanced task planning system developed by JPL for their Demonstration Testbed Project [4] referred to as the Remote Mission Specialist (RMS). The RMS has two stages of plan generation, stage one is responsible for converting high level directives into a series of commands which tell what specifically needs to be done in the task space. This series of commands is then used as an input to the second stage of the planner, where they are converted to primitives which are executable by the robot controller. This planning operation is constrained by the procedures and guidelines which must be stored in a knowledge base. Considerable knowledge engineering effort will be required to transform the generic and mission specific PCR operations into a form suitable for the AI computer system. All generated paths may be previewed with the use of graphic simulation before they are carried out. Thus, graphic motion simulation technology will also be required.

3.3 Telepresence Man-Machine Interface

The high-level user interface technology described above may not provide complete flexibility. For highly complex or spontaneous tasks, it may be more effective to operate the robot in the traditional teleoperator mode, with the operator controlling the motion of the end-effector with a joystick interface. The joystick controller should be a highly transparent interface allowing the operator to control the end-effector with the natural motion of his hand. He should be provided with the "look and feel" as seen at the end-effector, thus the term "telepresence".

Telepresence will be accomplished by providing the operator with visual and force feedback. Force feedback can be supplied by measuring the end-effector forces with available force transducers, and applying the corresponding force to the operators hand using powered actuators on the joystick controller. Visual information can be provided by the vision system cameras and additional optional cameras. Using a number of cameras, located on the robot or fixed within the PCR, several views of the robot arm, end-effector and work area can be provided.

Natural, telepresent control cannot be provided by a directly coupled master/slave controller. Current state-of-art man-machine interface technology is able to provide the above capabilities by using a control computer to act as a flexible interface between the joystick and the robot. The joystick position or motion is interpreted and transformed into suitable, corresponding robot commands. At the same time, the force on the end-effector or tool is interpreted, and transformed into suitable commands to the joystick to apply corresponding forces. Thus a universal, flexible bilateral controller is achievable.

With this flexibility a highly capable interface is achieved by providing force and motion scaling and filtering for vibrations. More importantly the reference frame for motion or forces can be selected to match the end-effector frame, the current display frame etc. Additional features such as position or velocity control and the ability to re-reference the joystick position will also be required. The technology to provide these capabilities has been demonstrated at a number of laboratories [7]. A bilateral controller of this nature will allow the operator to perform difficult tasks such as QD removal and insertion and other tactile-like assembly operations. Complete autonomy of these more difficult tasks is not readily achievable in a practical system and thus human intelligence and sensory capability is required. A universal controller provides an ideal augmentation human capability and is essential.

3.4 Control of Kinematically Redundant Manipulators

When a payload is mounted within the PCR or Shuttle bay a highly constrained and cluttered work area exists. This severely limits the ability to avoid obstacles using a 6 degree-of-freedom (DOF, ie. the number of actuators in the system) manipulator arm. The available obstacle free work area of the arm will be significantly increased using a redundant system with 7 or more DOF. This is due to the fact that the most general 6 DOF robot has at most 16 possible configurations for a given position and orientation (pose) of the tool or end-effector. Note, general here refers to a completely arbitrary set of fixed geometric constants which include the angle between each pair of adjacent axes (twist angles) and the fixed distance between adjacent links (offset dimensions) of the arm. Furthermore, most standard industrial robots, which contain all parallel or perpendicular adjacent axes have either two of four possible configurations for a given pose. This limited number of configurations may not provide obstacle free access for a required pose.

Introducing an additional link for the robot (an extra degree-of-freedom), provides an infinite number of robot configurations for a given pose of the end-effector. The human arm, containing 7 DOF (with respect to motion constraint not actuation), is an excellent example of a redundant manipulator. This is evidenced by examining the case of the hand placed firmly on a table. Without moving the position or orientation of the hand the elbow can be placed in an infinite number of locations.

Unfortunately algorithms for controlling redundant manipulators are now in the developmental stage. Most of the research is aimed at optimizing a given control parameter. Possibilities include minimizing energy, minimizing or balancing motor loads, maximizing the speed of motion, etc. These optimizations would be useful for on-orbit applications, where resources are limited. However, for ground operations these optimizations are not essential. The primary use of redundancy will be to provide obstacle free motion and increase the dexterity and available work area of the arm.

Thus, the key technology requirement is the development of obstacle avoidance and path planning techniques for the redundant system. Considerable advancement in this area may be required. However, certain techniques may naturally extend to the redundant case. For instance, the free path, configuration space technique described above (Section 3.1) can be implemented with a redundant system. The binary obstacle map represented in joint coordinates is simply a forward position analysis of the system which is easily accomplished regardless of the number of links in the system. However the binary map becomes a 7 (or more) dimensional space. This may become impractical to generate even offline, and search for free paths. Heuristic or rule based techniques may be necessary to provide manageable techniques which can be implemented with practical computer hardware. This is the single technology requirement in which existing capability may not be adequate.

4. SYSTEM DESCRIPTION

In this section the preliminary conceptual design and functionality of the PCR telerobotic system will be described. The system will consist of the following three major components: a manipulator capable of operation throughout the PCR, a hierarchical computer system and user interface, and sensor systems. The basic requirements of the system include the ability to perform inspection and other processing tasks. The system must not contaminate the Class IV clean room. Collision free motion must be guaranteed by a highly redundant, reliable obstacle avoidance system. Lastly, the system must be extremely easy to operate either in programmed or run-time control modes.

The manipulator will likely contain seven DOF to provide enhanced obstacle free motion capabilities. It will be mounted on a vertical rail attached to an existing structure in the PCR as shown in Figure 7. This will provide access to a majority of the payload area of the shuttle bay. The robot will provide approximately a 15 foot reach, 20 pound payload capacity and a positional accuracy of +/- 0.10 inch. A custom designed system with an optimized geometry for the required work area will be required. The arm will have to meet clean room requirements and all actuators must be explosion proof.

The end-effector will be designed to accommodate various tools, sensors and cameras. Quick connect tools may be used for some tasks. The video system may require special lens and filters, so they must also be designed for quick connect/disconnect. A multiple DOF articulated device may also be used to reach between the payloads and the bay.

The computer system will be a hierarchical, two layered architecture. The top high-level control computer will interact with the operator, and perform task planning, reasoning, programming and program storage and retrieval. The second layer contains the run-time control system. The high-level controller will most likely be an AI workstation, and the run-time controller will be a standard multi-processor computer environment. Various individual processors for sensors and end-effector systems will communicate with the run-time controller as well as the manipulator system. A joystick device will also be interfaced to this controller. A fully integrated system with all processing systems embedded within the controller would be ideal. However, this is unlikely to be possible. It may be possible to embed the manipulator servo controller since a custom system is being designed.

A majority of the computer processors will not have to be housed within the PCR. However, the operator workstation monitor, joystick controller and video displays should be located within the room for maximum viewing capability. All computer devices and displays located within the PCR will have to be industrialized systems to withstand the effects of launching.

The user interface consists of a joystick controller, video and simulation displays and the high-level controller workstation. The workstation will provide the primary interface to the system. The operator will have the capability of programming tasks by selecting generic descriptions of locations and devices from workstation menus. Taught or programmed tasks may be simulated graphically before actual execution. The work station will control the mode of the system (teleoperation, simulation, programmed task execution etc.) and provide required status. A force-feedback joystick controller will likely be required to perform assembly tasks. Thus the system will be capable of running in supervised teleoperation mode. Supervised meaning the obstacle avoidance system will continue to run in this mode.

A number of sensor systems of various complexity will be required. The obstacle avoidance system is based on two individual sensor systems as explained in Section 3. A 3D video image processing system will be required to recognize and determine the location and orientation of arbitrary objects. Also, the coordinates of carefully designed reference targets throughout the area will have to be determined. An arm based proximity sensing system will also be required to warn of impending collisions of any point on the arm. A hardware based system integrating a large number of small sensors mounted on the arm is envisioned. Each proximity sensor will be required to determine if a minimum distance, along a straight line, to the closest object of any material has been reached. Standard force/torque sensors will also be mounted on the end-effector.

5. DESIGN ISSUES

A number of major design issues will have to be addressed for the implementation of a telerobot system at the launch pad. The key issues include the following areas: arm geometry, system mounting and mobility, clean room requirements and, computer architecture and partitioning.

The kinematic structure or arm geometry (the fixed geometric parameters) of the robot must be designed to provide adequate access and dexterity, and allow obstacle free motion for number of applications and payloads. A six DOF arm could be designed to provide all desired positions and orientations of the end-effector in an uncluttered environment. However, in the highly constrained environment of the PCR, this may be impossible. As explained in Section 3.4, adding DOF to the robot provides an infinite number of configurations for a given end-effector pose. A detailed study using robot system workcell simulation and analysis tools will be required. Models of various payloads, the payload bay and the PCR will be used to determine the capabilities of various robot designs. A redundant system will only be implemented if a six DOF system cannot be designed to meet a majority of the desired tasks.

Because of the large dimensions of the payload bay, it would be impractical to design a stationary robot to provide the required access. Therefore the robot must be either allowed to move on vertical tracks or be easily transported to various locations within the PCR. To provide portability for the robot, it would have to be disassembled, re-assembled and calibrated before being used on the actual flight hardware. This greatly reduces the flexible capabilities of the system.

At this time, it appears that attaching vertical tracks to the PCR would provide the most effective coverage of the robot. However, the major drawback of tracks is the potential of it generating a large number of particulate contaminants because of the interaction of wheels against the track. This problem may be circumvented by placing protective covers over the track and the wheels.

Proximity sensors will be attached to the entire robot so that all links are instrumented for obstacle avoidance. The robot will incorporate explosion proof DC actuators with internal encoders, tachometers and fail safe brakes. The arm will also be designed to operate in a Class IV clean room. The above requirement makes actuator and drive system design a formidable task. All drive systems will have to be enclosed or gearless and may have to use dry lubrication to reduce contaminate generation. Possibilities include the use of harmonic drives, high-capacity step motors, direct drive motors, enclosed mechanisms or specialized motors.

The two layered computer architecture concept described in the above section will be adhered to. However, a number of specific design issues must be addressed. The two main computer systems will most likely communicate over a networked connection. The specific requirements and throughput rates of this connection must be established. The critical design issue then become the selection of a suitable network protocol. A uniform, easily maintained method of communicating and interfacing the various stand-alone processor systems to the run-time controller must be established. This is the only way to provide a reliable and flexible system capable of being expanded in a practical manner. Optimal selection of a suitable, standard bus structure (VME, MultiBus II, NUbus etc.) for the run-time controller, which will contain a large number of processors, is also a critical issue. Because the of the location of the PCR and its close proximity to the shuttle during lift-off, all equipment will have to be designed to withstand the associated shock, vibration and heat.

6. POTENTIAL APPLICATIONS

A multitude of tasks in the PCR are potential candidates for automation. These tasks include component inspection and verification, close-out photography, non-flight hardware identification, payload bay protective liner removal, lens cap removal, insertion and removal of QDs (quick disconnects), and insertion of small flight batteries and film packs.

These tasks can be divided into two categories, those tasks which do not require the robot end-effector to touch flight hardware, and those tasks which do. The first group of tasks eliminate all of the difficulties associated with force control. As long as the obstacle avoidance software works properly, there should be no physical interaction between the payload and the robot. This greatly reduces the risk factor associated with operating a robot in the PCR. However, many of the tasks which require contact provide the highest pay back.

Three tasks are of the highest priority, inspection of payload components for sharp edges, lens and dust cap removal, and insertion and removal of QDs. The first task is a non-contact in which astronauts personally check all payloads in the payload bay for sharp edges. Sharp edges could cause space suits to tear and depressurize. Currently, this requires special scaffolding to be erected so that the astronauts may thoroughly inspect the entire payload bay before close-out. A camera would be mounted on the end-effector, and the robot could either be controlled manually with the joystick, or automatically with the high level control software. Images of the payloads taken from the camera would be transmitted to a monitor and recorded for future reference.

On many payloads, a number of lens caps and dust covers are used to protect optical and other surfaces from contamination. Usually, these are the last non-flight items removed from the payload bay before closeout. Often, these protective covers are located in places with limited or non-existent access. In the past, technicians have walked on flight hardware to reach these locations and while nothing was damaged, the potential for damage and flight delay is great. The lens caps and dust covers must be designed for automation in the future. Presently, lanyards are attached to the lens caps and dust covers so that a technician can easily remove them by pulling on the lanyard. A visual target could be attached to the lanyard, and the integral vision system could identify and direct the robot to the target. Because the lanyard is compliant and will not transmit forces towards the payload, this task does not require extensive force control capabilities.

The third major task is the most difficult. Connecting and disconnecting QDs requires extensive force control capabilities coupled with object identification, positioning, and path planning. Currently, the Robotic Applications Development Laboratory (RADL) at KSC is involved in automated QD insertion for remote umbilical connections. This research has demonstrated successful target acquisition and insertion of a QD into a receptacle. The QDs include fluid, gas, power, and communication connections. The QDs are located about the complete periphery of the payload, and are often located in inaccessible locations. For example, the upcoming Magellan has over 50 QDs in various locations. QDs designed for automation greatly simplify the required robotic capabilities. For example tapered shanks, self aligning and automatic locking QDs which incorporate common design for different missions will improve the robot capabilities and help to reduce processing costs.

7. CONCLUSION

Payload and shuttle processing tasks within the PCR represent an ideal opportunity for improvements through the use of physical automation and telerobotic technology. A reliable, easy to use manipulator system capable of providing access to a large portion of typical payloads within the shuttle bay will reduce processing costs and potential contamination, and improve safety and cleanliness. Additionally, the implemented technologies and system designs will also provide similar benefits to both on-orbit and ground processing of the Space Station Freedom. A number of advanced technologies will have to be integrated in the proposed system. However, these technologies have been developed and are currently undergoing refinements in full scale demonstration programs, greatly reducing the associated risks.

The advanced technologies and capabilities required for the proposed telerobotic system include a redundant obstacle avoidance system, intelligent task planning and reasoning, high level user programming interface, force feedback joystick control and potentially, redundant arm control. This system represents an optimal balance between system autonomy and human intervention based on todays technical capability. Inherent in this augmented or balanced system design is the ability to evolve to a higher degree of autonomy. An initial implementation capable of performing simple placement and scanning tasks, without joystick control capability can be implemented in a 2-3 year period. A complete implementation is possible within 5 years. The completed system will represent effective and rapid use of NASA developed, state-of-the-art automation technology.

REFERENCES

1. Space Station Processing Facility Automation and Robotics Study, WO-P0005, McDonnell Douglas Astronautics Company, Kennedy Space Center, Florida, 1987.

2. Gary Sweet, Leonard Hutto, Robots Refurbish Space Shuttle Hardware, SME-RI Robots 11 Proceedings, 1987, p 11:9-28.

3. Dan Wegerif, Mike Sklar, Plan For JPL/KSC Telerobot PCR Demonstration, McDonnell Douglas Astronautics Company, Kennedy Space Center, Florida, 1988.

4. Steve Peters, Carol Collins, David Mittman, Jacquelyn O'Meara, Mark Rokey, Planning and Reasoning in the JPL Telerobot Testbed, Jet propulsion Laboratory, California Institute of Technology, Pasedena, California, 1988.

5. Tomas Lazano-Perez, Spatial Planning: A Configuration Space Approach, IEEE Transactions on Computers, Vol. c-32, No. 2, February 1983, pp. 108-120.

6. Brian Wilcox, D. Gennery, B. Bon, T. Litwin, The Sensing and Perception Subsystem of the NASA Research Telerobot, Proceedings of the Workshop on Space Telerobotics, JPL publication 87-13, p 3-8.

7. D. Tesar, H. Lipkin, Assessment for the Man-Machine Interface Between the Human Operator and the Robotic Manipulator, (NSF Grant No. ENG78-20112 and DOE Contract No. ER-78-S-05-6102), Univ. of Florida, 1979.

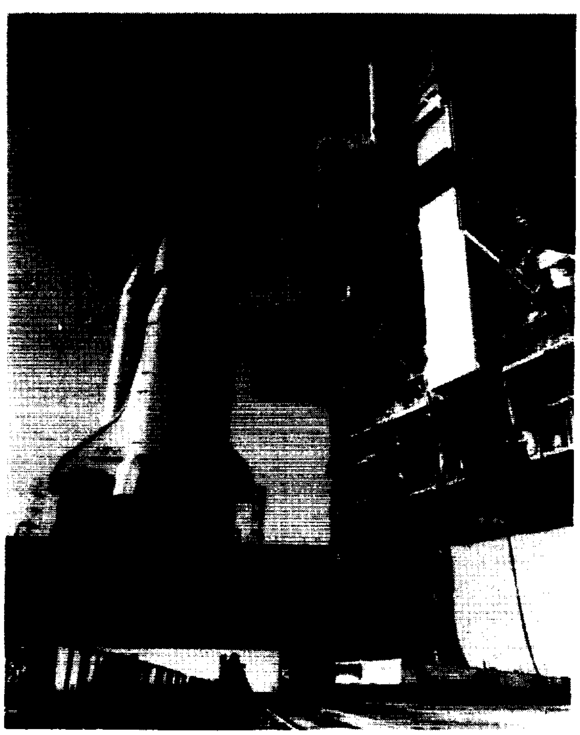

Figure 1. STS, RSS, Payload Canister And PCR

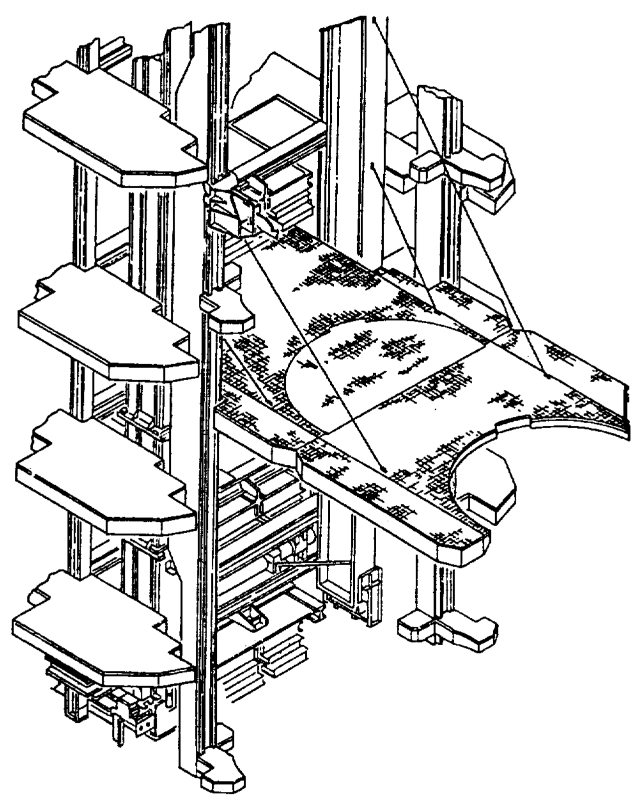

Figure 2. Payload Changeout Room

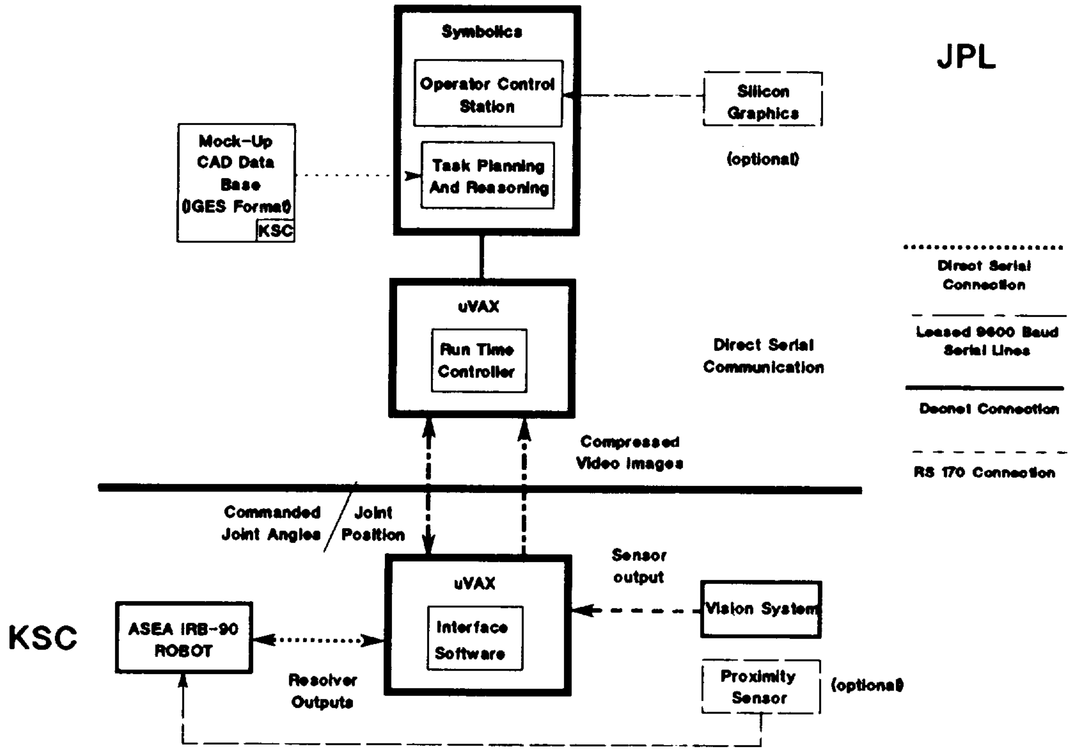

Figure 3. KSC/JPL Hardware and Communications For Remote Operations

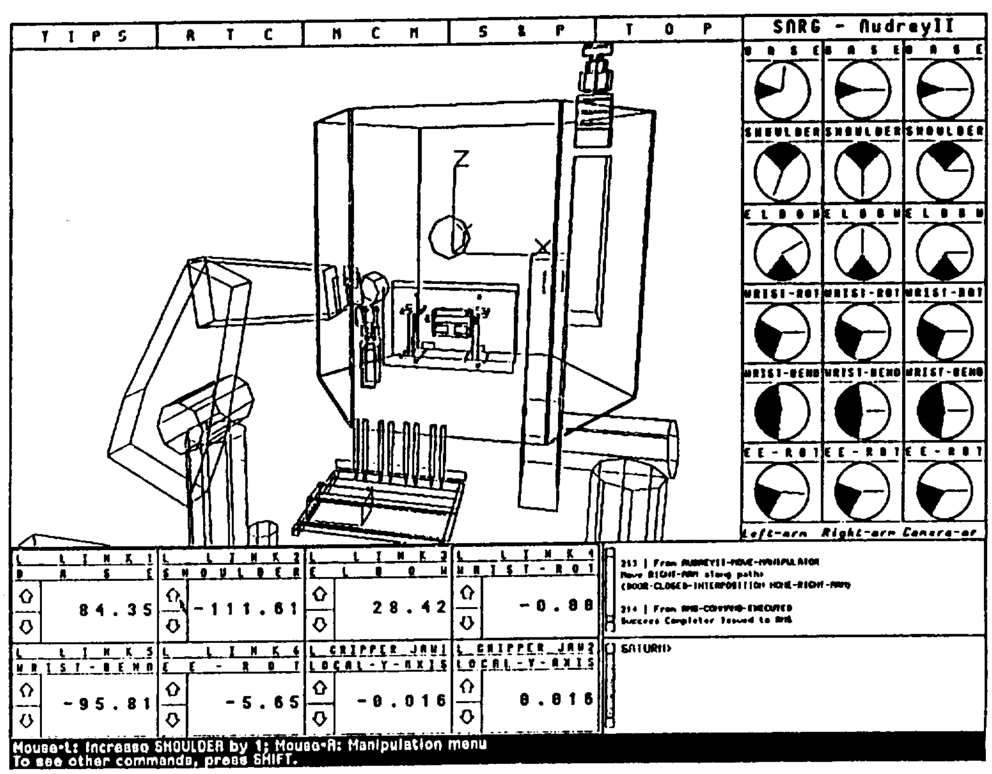

Figure 4. Current JPL Teleoperator User Interface

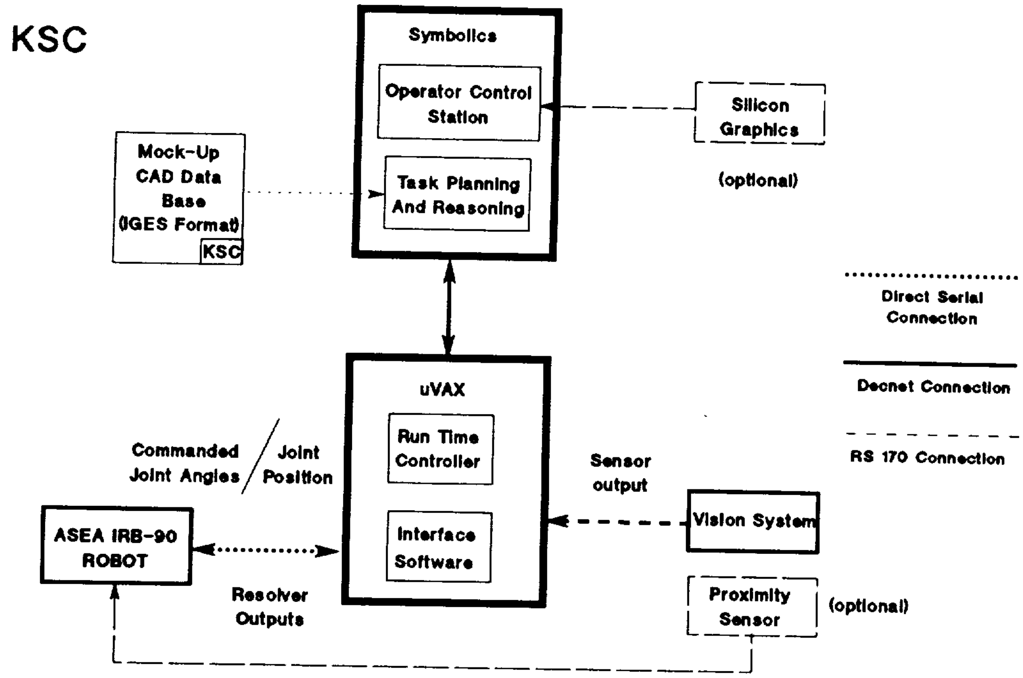

Figure 5. KSC/JPL Hardware and Communications for Direct Operations

Figure 6. PAM-D Payloads Mounted In STS Payload Bay

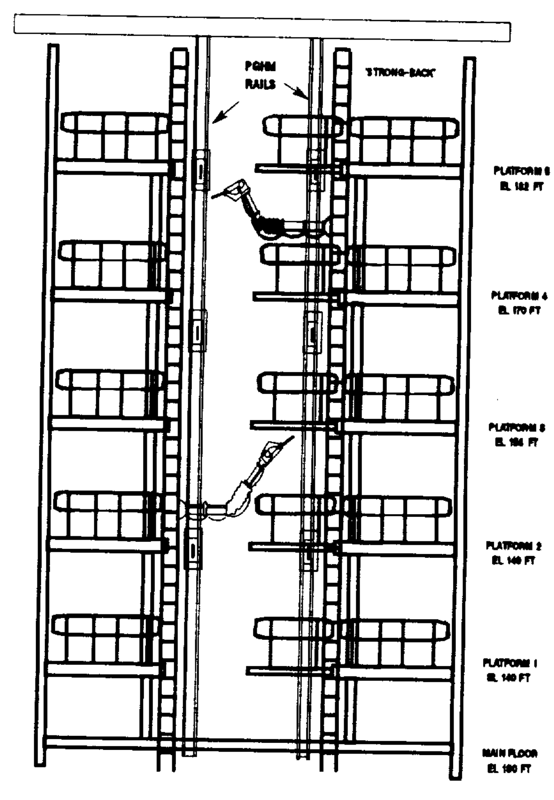

Figure 7. Conceptual Design of Manipulator Located In The PCR